Stream temperature responses to clearcut logging in the central interior of British Columbia: test of the predictive model developed by Mellina et al. (2002)

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Mountain Pine Beetle Initiative
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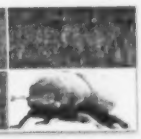

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Abstract

Water temperature is a key factor regulating physical and biological processes in small streams, and streamside logging often results in increased summer temperatures that can be detrimental to resident fish. Recently, Mellina et al. (2002) developed a model to predict downstream temperature trends in small headwater and lake-headed streams using easily measured predictors. During this study, summertime stream temperature and canopy cover data collected from 20 lake-headed and headwater streams in north-central B.C. were used to subject the model to an independent test to assess its predictive capabilities across space and time. The temperature data revealed that downstream cooling was widespread among the lake-headed streams, and downstream warming was prevalent in the headwater streams, regardless of whether or not the riparian zones were harvested. The data also suggested that temperature increases following streamside timber harvesting around lake-headed streams were more modest when compared to headwater streams, and that these increases were likely mitigated by a combination of warm outlet temperatures (promoted by the presence of the lakes) and cold groundwater inputs. Using complete summertime data, the cooling model predicted with relative accuracy the average daily downstream cooling or warming in the study streams (with deviations ranging from 0.02°C to 0.96 °C), and it continued to be relatively accurate when using data from restricted summertime intervals (with deviations ranging from 0.01°C to 2.53 °C). Because large-scale clearcut logging is often the only effective control for severe mountain pine beetle infestations in epidemic areas, the model has the potential to become a powerful and cost-effective risk management tool that may help managers plan appropriate timber harvesting activities that will minimize the potential impacts on stream-dwelling fish. The independent testing provided by this study will likely increase confidence in the model's application to management issues.

Résumé

La température de l'eau est un facteur clé qui régule les processus physiques et biologiques dans les petits cours d'eau, et la récolte de bois en bordure des ruisseaux entraîne souvent des augmentations de température de l'eau en été qui peuvent être nuisibles aux poissons résidents. Mellina et coll. (2002) ont récemment élaboré un modèle prédictif des tendances de la température en aval dans les petits cours d'eau d'amont et dans ceux prenant leur source dans des lacs, fondé sur des paramètres de prévision faciles à mesurer. Pour cette étude, des données sur le couvert et les températures estivales de cours d'eau dans leur cours supérieur ou provenant de lacs ont été collectées pour 20 cours d'eau situés dans le centre nord de la Colombie-Britannique. Ces données ont été utilisées pour soumettre le modèle à un essai indépendant visant à évaluer ses fonctions de prédiction dans l'espace et le temps. Les données sur la température ont révélé qu'un refroidissement en aval était fréquent dans les cours d'eau prenant leur source dans des lacs alors qu'on constatait généralement un réchauffement en aval fréquent dans les cours d'eau d'amont, que des récoltes aient eu lieu ou non dans les zones riveraines. Ces données ont aussi suggéré que les augmentations de température des zones riveraines dont le bois a été récolté, près des cours d'eau en provenance d'un lac, étaient moindres par rapport à celles constatées autour des cours d'eau d'amont, et que ces augmentations semblaient atténuées par une combinaison d'eaux chaudes à la décharge (à cause de la présence des lacs) et d'eaux froides souterraines. En utilisant des données estivales complètes, le modèle de refroidissement a prédit avec une précision relative la moyenne quotidienne du refroidissement ou du réchauffement en aval des cours d'eau à l'étude (avec des écarts allant de 0,02 °C à 0,96 °C). Il est resté relativement précis lorsqu'on a utilisé des données provenant de périodes estivales restreintes (avec des écarts allant de 0,01 °C à 2,53 °C). Les coupes à blanc à grande échelle étant souvent le seul moyen efficace pour réprimer les foyers d'infestation grave du dendroctone du pin ponderosa, ce modèle pourrait constituer un outil de gestion du risque puissant et rentable pour aider les gestionnaires à planifier des activités de récolte du bois adéquates qui minimiseraient les répercussions potentielles sur les poissons vivant dans les cours d'eau. L'essai indépendant fourni par cette étude permettra sans doute d'envisager avec confiance l'application de ce modèle à des problèmes de gestion.

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Introduction

Water temperature is one of the most important factors regulating physical and biological processes in small streams (Beschta et al. 1987). Logging to stream banks, with the subsequent reduction in overhead canopy cover, can alter the thermal characteristics of streams, and in many cases can result in increased summer and decreased winter stream temperatures (Hicks et al. 1991). Because temperature affects many stream biological processes, it is often a key consideration when planning timber harvesting within riparian zones (as shown by the priority placed by the current British Columbia Forest and Range Practices Act on identifying "temperature sensitive streams").

A stream's temperature is governed by its energy budget (Evans et al. 1998). Direct solar radiation is often the major source of energy (Brown 1969), but other processes can temper its influence (Adams and Sullivan 1989; Sinokrot and Stefan 1993; Evans et al. 1998). Processes at the air–water interface include energy transfers due to evaporation, sensible heat transfer, condensation, and precipitation, while channel-bed processes include energy exchanges via conduction through the stream bed, advective transfers through groundwater inputs, and friction. The size and direction (input or output) of the different energy components will determine whether or not a stream warms or cools as it travels downstream (Sinokrot and Stefan 1993). In small, forested streams, heat transfers through net radiation, evaporation, convection and conduction are relatively insignificant, as the adjacent riparian vegetation not only provides shade from direct sunlight but also limits wind movement immediately above the stream (Brown 1985; Adams and Sullivan 1989). By contrast, timber harvesting that removes riparian vegetation increases the exposure of a stream and its bed to direct solar radiation, often resulting in increased maximum temperatures and diurnal fluctuations (Brown 1985; Brownlee et al. 1988; Hostetler 1991). These consequences become particularly evident if the increase in radiation overwhelms the energy budget components that contribute to cooling (for example, evaporation and groundwater inputs; Brown 1985). The degree to which stream temperatures respond to clearcut harvesting also depends on other factors (such as the discharge and temperature of any groundwater inputs, the discharge of the stream, the composition of the streambed, and the percentage of the drainage area that is logged), with small streams generally responding more rapidly to energy inputs than large streams (Brown 1969; Brown and Krygier 1970; Evans et al. 1998).

Evidence from the literature appears to support the general conclusion that streamside timber harvesting results in increased summer maximum temperatures (with increases as large as 15.8 °C being reported by Brown and Krygier 1970), as well as increased diurnal fluctuations (see reviews in Anderson 1973, Beschta et al. 1987, and Hicks et al. 1991). However, the majority of published studies that have examined stream temperature responses to logging have focused on headwater streams, with little attention paid to streams headed by lentic waterbodies (lakes and swamps). Potential differences in the thermal regimes of headwater versus lake-headed streams warrant a distinction. For example, Mellina et al. (2002) found that small lake-headed streams in north-central British Columbia (B.C.) underwent only modest changes (averaging 0.05 °C – 1.1 °C) with respect to summer daily maximum and minimum temperatures, diurnal fluctuations, and stream cooling following streamside timber harvesting, compared to increases of ~5 °C – 7 °C that have been reported in the literature for headwater streams. Furthermore, the authors found that lake-headed streams were naturally (i.e., when unharvested) ~ 6 °C – 11 °C warmer during the summer when compared to headwater streams and groundwater sources, and that these stream types generally cooled as they flowed downstream (regardless of whether or not streamside logging had taken place). The observed downstream cooling in their study streams was attributed to a combination of warm initial temperatures (promoted by the presence of headwater lakes and swamps) and cold groundwater inputs, factors that also likely contributed to the observed modest temperature changes following clearcut logging. By comparison, the temperatures of headwater streams generally rise as they flow downstream during summer months, even in fully shaded channels, as relatively cold initial stream temperatures are warmed

as a result of exposure to warm air and incoming radiation, and because of decreases in the relative contribution of cold groundwater inputs (Sullivan et al. 1990; Zwieniecki and Newton 1999).

Predicting stream temperature responses is a potentially complex undertaking given the myriad possible interactions among energy budget components (Adams and Sullivan 1989), and previously published models and energy budget calculations require extensive hydro-meteorological data (e.g., see Brown 1969, Sinokrot and Stefan 1993, and Evans et al. 1998). However, Mellina et al. (2002) developed a model to predict downstream temperature trends in small headwater and lake-headed streams using easily measured predictors. Specifically, their model (henceforth referred to as the cooling model) predicts the average amount of daily summertime stream cooling that can be expected between an upstream (US) and downstream (DS) boundary. Stream cooling is defined here as the difference between US and DS mean daily temperatures, and is positive if a stream cools as it travels downstream and negative it if warms. Summertime (defined here as the period between June 01 and August 31) is generally the period of most interest to fisheries and forestry managers, because the impacts of clearcut logging on stream temperatures are expected to be greatest during the summer months. The cooling model was developed using stream temperature and physical data from 14 streams located in north-central B.C., and requires input from two predictors (the maximum temperature at the US site and the average amount of shading between study boundaries). The model has the following form:

(1) $\text{Cooling} = -9.9 + (0.25 \bullet \text{Max } T_{US}) + (4.0 \bullet \text{Log}_{10} \text{Canopy cover})$ ($R^2 = 0.95$, $n = 14$, $P < 0.001$)

Cooling is defined above and has units of °C, max T_{US} is the average summer maximum temperature recorded at the US site (°C), and canopy cover is the average amount of shade provided by the riparian vegetation (%). The model indicates that downstream cooling or warming is highly dependent on the maximum temperatures recorded at an upstream boundary and on the amount of shading provided by riparian vegetation, and it was relatively accurate at predicting the amount of cooling observed in the study streams that comprised the model development dataset (with an average absolute deviation of 0.3 °C from the line of correspondence; Mellina et al. 2002). Although the model predicts downstream cooling or warming, the average summertime daily mean temperature at a downstream site can also be calculated by adding the amount of predicted cooling or warming to the daily mean upstream temperature.

Despite the relative accuracy of the model's predictions, Mellina et al. (2002) caution that it likely only applies to streams that fall within the range of temperatures and physical characteristics encountered in their model development dataset. Furthermore, although the authors provide some measure of independent spatial and temporal testing, the accuracy of the model's predictions as it relates to streams other than those used in the model's development, as well as streams in different geo-climatic regions, remains largely unknown. Based on their results and conclusions, the primary objectives of this study were therefore: a) to assess the generality of downstream cooling (as opposed to warming) in lake-headed streams; b) to assess whether post-logging temperature increases are reduced in lake-headed streams when compared to headwater streams; c) to subject the predictive cooling model to an independent spatial and temporal test to assess its reliability and predictive capabilities across space and across time; and d) to determine the amount of stream cooling that can result from mixing surface waters with groundwater inputs.

Materials and methods

Study design

All four objectives were accomplished using a comparative survey comprising 20 streams located within the sub-boreal spruce biogeoclimatic zone of north-central B.C. (Farley 1979; Figure 1). This region is dominated by glaciolacustrine and sandy glaciofluvial soils, with an average annual precipitation of ~ 50 cm falling primarily as snow between November and March, and rain between April and October (Macdonald et al. 1992). The highest stream discharges occur in spring as a result of snowmelt, and the lowest discharges typically occur during winter and during the month of August (Beschta et al. 1987; Brownlee et al. 1988). The 20 streams, of which five were monitored by the B.C. Ministry of Forests, lie within the Fraser River and Nation River watersheds, and were chosen to encompass the range of physical characteristics that are commonly encountered in north-central B.C. The streams comprised both headwater and lake-headed types (including one stream headed by a swamp), and they were generally small (between 0.8 m and 6.8 m in bankfull width) with gradients ranging from 0.8 % to 11% and with distances between the US and DS boundaries ranging from 190 m to 725 m (Table 1, next page). No tributaries were encountered within the stream study sections. The headwater lakes and swamp were also small (< 32 ha), with distances from the lake and swamp outlets to the US study boundaries ranging from 30 m to 1250 m (Table 1).

Figure 1. Map showing the general location of the streams monitored during this study.

The 20 streams were further divided into forested (i.e., old growth) and logged categories. Forested streams were those around which no logging activities had taken place, whereas logged streams were subjected to logging within their riparian zones (defined as a zone extending 30 m perpendicularly from each stream bank; Anonymous 1995). Logging activities were conducted between 1971 and 2002 (Table 1), and except for streams Bridge, 118/48, and 118/16, comprised clearcut logging to both stream banks that did not include the retention of riparian buffer strips. Timber harvesting within the riparian zones of the above three streams consisted of clearcut logging that removed only mature commercial timber, with the majority of non-commercial and deciduous timber left standing to continue providing shade and future recruitment of large organic debris. By comparison, the remaining cutblock areas of these three streams were completely clearcut.

Table 1. Physical characteristics of the streams monitored during this study.

Stream	Drainage	Bankfull width (m)	Stream gradient (%)	Aspect	Study length (m)	Canopy cover (%)	Lake surface area (ha)	Distance from US site to outlet (m)	Year logged	Stream number
Headwater streams: forested										
RB8	Fraser	2.1	2.5	NE	500	82.5	n/a	n/a	n/a	1
Rot1	Nation	2.7	7.7	W	500	90.9	n/a	n/a	n/a	2
T10	Nation	3.6	4.5	SW	500	81.6	n/a	n/a	n/a	3
DV1	Fraser	3.9	8.5	SE	500	88.3	n/a	n/a	n/a	4
Bowron C1*	Fraser	1	1.1	n/m	209	63.6	n/a	n/a	n/a	5
Bowron T1*	Fraser	2.2	1.2	n/m	190	71.8	n/a	n/a	n/a	6
Bowron T2*	Fraser	0.9	1.7	n/m	241	74.4	n/a	n/a	n/a	7
Bowron T3*	Fraser	0.8	7	n/m	261	77.2	n/a	n/a	n/a	8
Chuchinka*	Fraser	1.7	0.8	n/m	725	62.5	n/a	n/a	n/a	9
Headwater streams: logged										
Thursday	Fraser	6.8	4.7	NE	500	40.1	n/a	n/a	1971	10
SK2	Fraser	2.3	3	S	500	81.5	n/a	n/a	1993	11
Emily2	Fraser	1.7	2.7	S	500	89.1	n/a	n/a	1991	12
Lake-headed streams: forested										
Willow 6‡	Fraser	3.3	3.2	W	500	79.3	9.5	100	n/a	13
Airline	Nation	2.7	2	NE	500	81.9	31.2	50	n/a	14
T12.5	Nation	3.2	3.3	S	500	73.9	14.6	100	n/a	15
Keves	Fraser	3.3	11	NW	500	85.9	11.2	160	n/a	16
Lake-headed streams: logged										
Bridge	Nation	2.1	2.3	SE	535	65.3	18.3	30	2002	17
118/48†	Nation	1.7	1.9	SW	607	62.8	15.3	200	1998	18
118/16†	Nation	1.7	1.8	SE	372	64.8	13.1	60	1998	19
Whitefish	Fraser	1.9	10.7	NE	350	28.9	7.4	1250	1992	20

Note: *denotes streams monitored by the B.C. Ministry of Forests (Mr. Dave Maloney), †denotes the case-study streams previously monitored by Mellina et al. (2002), and ‡denotes streams headed by a swamp. n/m stands for "not measured", and n/a for "not applicable".

Stream temperature monitoring, physical characteristics, and determination of groundwater inflows

Automated temperature loggers (range –5 °C to 35 °C, resolution 0.2 °C, accuracy 0.3 °C) were installed in all 20 streams in late May 2002 at both the US and DS boundaries to record hourly water temperatures, and were removed in early September 2002. For all logged streams, the US and DS sites were at the uppermost and lowermost edges of the cutblock boundaries, respectively, and assessments of the impacts of timber harvesting on stream temperatures therefore only apply to DS sites (as the US sites were unaffected by logging). All of the data loggers were anchored in pools to ensure they would remain submerged during the low-flow period.

Stream bankfull width, gradient, canopy cover, and aspect were measured during the month of August 2002 according to the methods outlined in Ralph (1990). Five measurements of bankfull width, gradient, and canopy cover were taken at equidistant locations along the study sections and averaged for each stream, whereas aspect was measured at a single point along each study section. Canopy cover represents the amount of stream shading provided by the riparian vegetation and was measured immediately above the stream surface with a hand-held densiometer. Canopy covers ranged from 63 % to 91% and from 40% to 89% in the forested and logged headwater streams, respectively, and from 74% to 86% and 29% to 65% in the forested and logged lake-headed streams, respectively (Table 1).

To determine the amount of groundwater entering the stream study sections, a single discharge measurement was obtained at the US and DS boundaries of 15 streams during the month of September 2002 during periods of no rain using constant-injection salt dilution gauging (Johnstone 1988). This method is relatively simple and inexpensive to carry out, is ideally suited for low flows because the instruments do not rely on stream velocity, and is relatively accurate (+/- 5%; Johnstone 1988). Because no tributaries entered the study reaches of these 15 streams, differences in flow between US and DS sites should equal net groundwater inputs. Discharge was not measured in the five headwater streams monitored by the B.C. Ministry of Forests.

Data analysis: comparisons between lake-headed and headwater streams

In order to examine general temperature patterns, the daily summertime (June 01 to August 31) mean, maximum, and minimum temperatures, as well as the daily fluctuations (defined as the daily maximum – minimum temperatures) were calculated from the hourly data for the US and DS sites of all 20 streams. To assess the generality of downstream cooling in lake-headed streams, the daily DS cooling or warming (defined above) was also calculated for each stream. In order to assess differences or similarities among the four stream categories (forested or logged, lake-headed or headwater), the downstream daily temperature trends were averaged within each category and plotted. Lastly, the difference in summertime averages for each DS temperature trend between the forested and logged states of the headwater and lake-headed streams was calculated in order to examine whether post-logging temperature changes differ among these stream types.

In addition to the comparative approach described above, summertime pre- (2001) and post-logging (2002) temperature data from lake-headed Bridge Creek (a stream that was also included in the comparative survey) were used to test the hypothesis that post-logging temperature increases are reduced in lake-headed streams when compared to headwater streams. The riparian zone of Bridge Creek was harvested during early 2002 using the selective logging treatment described above (and which was also applied to lake-headed streams 118/48 and 118/16 in 1998). Because temperature patterns at the DS sites (those affected by logging) were highly correlated with temperatures at the US (control) sites, relations between summertime US and DS temperatures during the pre-logging phase were used as benchmarks against which the magnitude of any post-logging changes could be assessed. Following the statistical methods outlined in Mellina et al. (2002), relations between summertime (June 01 to August 31) US and

DS daily mean, maximum and minimum temperatures, as well as daily fluctuations, were assessed for the pre-logging period using linear regression analysis. Relations between daily US maximum temperatures and stream cooling were similarly assessed. This was followed by the construction of 95% prediction intervals around the regression lines to encompass approximately 95% of the observations (Neter et al. 1990). Summertime post-harvest temperature relations among the same variables were computed in a similar manner, and the results were superimposed on the pre-harvest regressions and prediction bands. Post-harvest observations deviating from the temperature patterns established during the pre-harvest period were attributed to the logging treatment. Mean net differences between observed post-harvest temperatures and those predicted by the pre-harvest regressions were then calculated to assess the average magnitude of any post-logging changes.

Data analysis: tests of the predictive cooling model

To test the cooling model's predictive capability across space (i.e., how accurate are the model's predictions for streams other than those used in the model's development), average summertime (June 01 to August 31) maximum US temperatures recorded in 2002, as well as the average riparian canopy cover between the US and DS study boundaries, were calculated for 18 of the 20 streams (lake-headed streams 118/48 and 118/16 being excluded). Data from these 18 independent streams were substituted into the cooling model, and its predictions were compared against the observed cooling (or warming) that occurred in each stream. Temperature and canopy cover data from the two excluded streams (which were previously monitored during 2001 by Mellina et al. (2002) and which formed part of the model's original development dataset) were used to test the cooling model's predictive capability across time (i.e., how accurate is the model when applied to the same stream over different years).

To determine the amount of stream cooling that can result from mixing surface waters with groundwater inputs, the following mixing model (based on Brown 1985) was applied to the 15 streams from which discharge data were collected:

$$(2) \qquad \Delta T = T_{US} - T_{DS} = \frac{Q_{DS} - Q_{US}}{Q_{DS}} (T_{US} - T_{GW})$$

where T_{GW} is the groundwater temperature (°C), T_{US} and T_{DS} are average summer daily mean temperatures at the US and DS boundaries (°C), and Q_{US} and Q_{DS} are discharges measured at the upstream and downstream ends of the study reaches ($L \cdot s^{-1}$). The overall mean summer temperature of four seepages monitored by Mellina et al. (2002) and equaling 6.75 °C was assumed to represent regional groundwater temperatures, and was substituted for T_{GW} in all mixing model iterations. Comparisons between the predictive capabilities of the Mellina et al. (2002) cooling model and the Brown (1985) mixing model (both of which predict downstream cooling or warming) were also made.

Because the cooling model developed by Mellina et al. (2002) relies on temperature data collected over a period of three months (a potentially unrealistic requirement if it is to be used for management purposes), the model was further tested by assessing how accurately it could predict each stream's average summertime cooling or warming using restricted temperature data. To simulate a situation where data from only a single month were available to fisheries and forestry managers, average monthly maximum US temperatures for June, July, and August 2002 were calculated for each stream and substituted into the model (for a total of 60 iterations), and its predictions were compared against the observed average downstream cooling or warming that occurred in each stream over the entire summer. Secondly, to simulate a situation where data from only a single day were available, for each stream the maximum US temperatures from the 5th, 15th, and 25th day of each of the three summer months were substituted into the model (for a

total of 180 iterations), and its predictions were again compared to each stream's observed average summertime cooling or warming. The range in days was chosen to allow for the identification of the period during the summer that would produce the most and least accurate predictions in cases where sampling could only take place over the course of a single day. Stream-specific canopy cover estimates obtained in August 2002 were retained for the model iterations using restricted data, as monthly and daily measurements were not taken to coincide with the test periods.

Lastly, a new predictive cooling model (henceforth referred to as the global model) was developed using average summertime maximum US temperatures and canopy cover data from the 14 streams monitored by Mellina et al. (2002) in 2001 (and comprising the original model development dataset) combined with data from the 18 independent streams monitored during this study in 2002. The global model (with a sample size of 32 streams) was constructed to support the validity and robustness of the original model (which had a sample size of 14 streams) through comparisons of model R^2 values and standard errors of the estimate, as well as model intercepts, predictor coefficients and significance levels. Further validation of the global model was undertaken using the prediction sum of squares (PRESS) procedure (Neter et al. 1990). This procedure involved 32 iterations whereby each stream's average summertime cooling was predicted from a regression model developed using the remaining 31 streams, with the results being used to generate a PRESS value for the global model. The precision of the global model's predictions was assessed by comparing its sum of squares error (SSE) with the PRESS value obtained using the above procedure (Neter et al. 1990), as well as through comparisons between predicted and observed downstream cooling for each stream.

Results

Comparisons between lake-headed and headwater streams

The temperature patterns of the 20 streams monitored during this study revealed that lake-headed streams were naturally warmer at their US (control) sites when compared to the US sites of headwater streams, with lake-headed streams exhibiting average summertime daily mean, maximum and minimum temperatures, and daily fluctuations, of 13.0 °C, 14.7 °C, 11.4 °C, and 3.3 °C, respectively, compared to 7.4 °C, 8.2 °C, 6.7 °C, and 1.6 °C for headwater streams. Furthermore, the majority of headwater streams (8 out of 9 in the forested, and 2 out of 3 in the logged categories) exhibited downstream warming, whereas the majority of lake-headed streams (all in the forested, and 3 out of 4 in the logged categories) exhibited downstream cooling (Table 2). When comparing temperature trends at the DS sites (those affected by logging), the logged headwater and lake-headed streams were generally warmer and exhibited greater daily fluctuations than their forested counterparts (Table 2, Figure 2), and there were similar average summertime temperature differences between forested and logged streams within the lake-headed and headwater categories (Table 3). However, canopy covers were reduced by an average of ~ 31% in logged versus forested lake-headed streams, compared to reductions of only ~ 9% in logged versus forested headwater streams (Table 3).

Table 2. Summertime average daily mean, maximum, and minimum temperatures (°C) recorded at the upstream (US) and downstream (DS) sites of the streams monitored during 2002. Average daily fluctuations (maximum – minimum) and downstream cooling (daily mean US – DS temperatures) (°C) are also included for each stream. Positive (negative) values for stream cooling indicate that the stream cooled (warmed) through the study section. Summer is defined as the period from June 01 to August 31.

	Upstream				Downstream				
Stream	Mean	Maximum	Minimum	Fluctuation	Mean	Maximum	Minimum	Fluctuation	Cooling
Headwater streams: forested									
RB8	7.81	8.9	6.81	2.09	7.97	9	7.02	1.98	-0.15
Rot1	5.74	6.25	5.29	0.96	5.8	6.25	5.41	0.84	-0.06
T10	5.78	6.63	5.14	1.49	5.97	6.76	5.33	1.43	-0.2
DV1	6.25	7.29	5.28	2.01	6.32	7.23	5.48	1.74	-0.07
Bowron C1	7.55	7.98	7.12	0.85	7.58	8.09	7.12	0.97	-0.02
Bowron T1	9.32	10.11	8.53	1.59	9.3	10.01	8.55	1.46	0.02
Bowron T2	7.75	8.22	7.28	0.94	7.8	8.24	7.35	0.89	-0.05
Bowron T3	6.02	6.3	5.76	0.54	6.43	6.72	6.12	0.59	-0.41
Chuchinka	9.27	10.08	8.5	1.59	9.64	10.56	8.85	1.71	-0.37
Headwater streams: logged									
Thursday	9.11	10.87	7.65	3.22	9.27	11.28	7.73	3.55	-0.16
SK2	7.28	8.55	6.31	2.24	7.15	8.11	6.36	1.75	0.13
Emily2	7.26	7.98	6.57	1.41	7.46	8.14	6.78	1.36	-0.2
Lake-headed streams: forested									
Willow 6	13.4	14.59	12.07	2.52	12.54	13.69	11.15	2.54	0.87
Airline	14.37	16.03	12.86	3.17	12.58	13.68	11.62	2.05	1.79
T12.5	11.19	12.74	9.76	2.99	10.45	11.74	9.25	2.49	0.74
Keves	12.6	14.02	11.28	2.74	10.61	11.57	9.66	1.91	1.99
Lake-headed streams: logged									
Bridge	15.98	17.57	14.44	3.13	13.59	15.33	11.83	3.5	2.39
118/48	14.77	16.6	13	3.61	13.05	14.71	11.36	3.35	1.72
118/16	14.41	18.11	11.13	6.98	13.08	16.07	10.38	5.69	1.33
Whitefish	7.27	7.99	6.61	1.39	8.37	10.1	7.08	3.03	-1.1

Figure 2. Daily mean, maximum, and minimum temperatures recorded at the downstream sites of the 20 streams monitored during this study grouped into four categories (lake-headed or headwater, forested or logged). Mean daily fluctuations (daily maximum – minimum temperatures), as well as mean daily downstream cooling (daily mean upstream – downstream temperatures), are also shown. For each temperature trend, data were averaged within each of the four categories (with the number of streams in each category shown in the legend), and correspond to the period from June 01 to Aug. 31 2002.

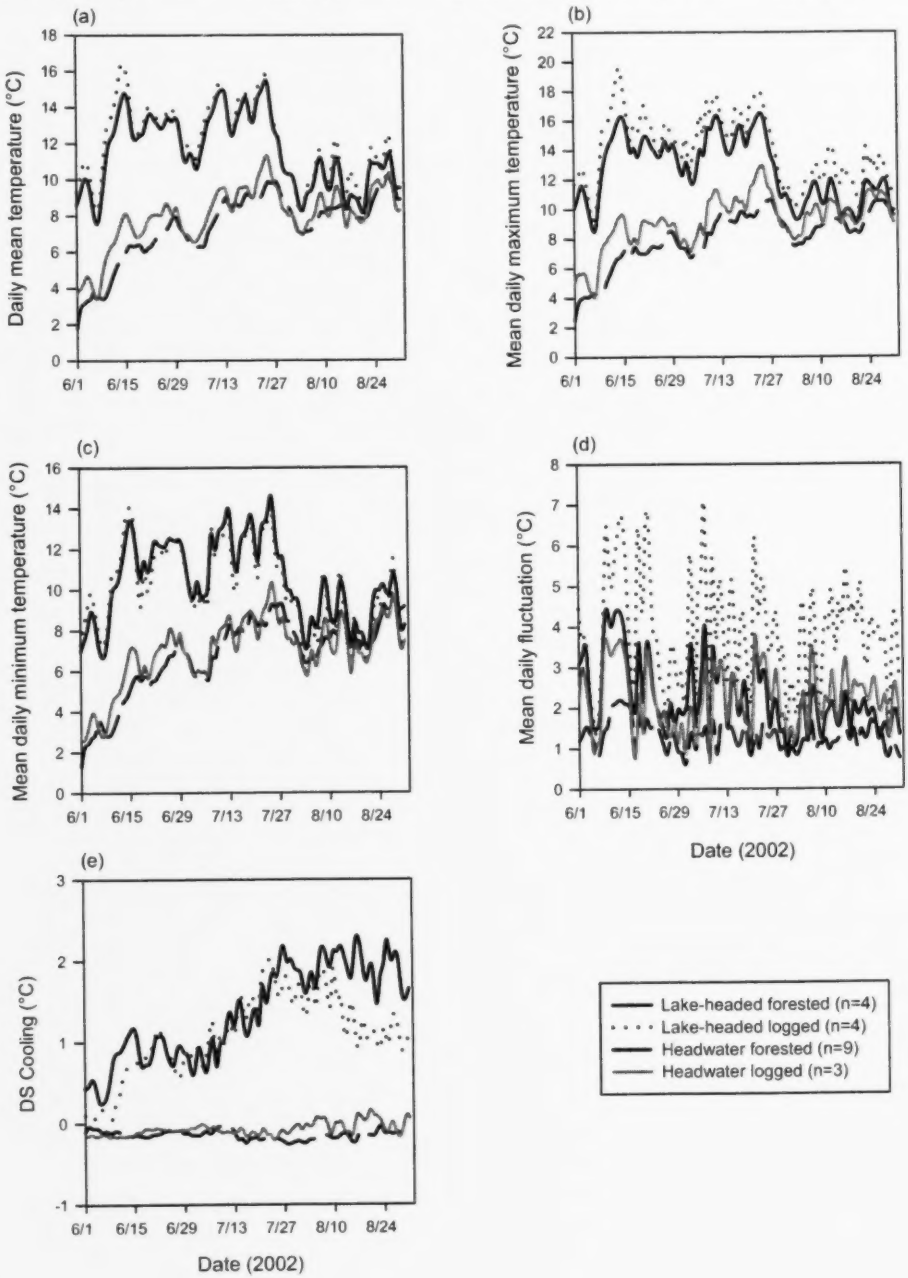


Table 3. Canopy cover, and average summer daily mean, maximum, and minimum temperatures (°C) recorded at the downstream sites of the study streams and grouped into four categories (lake-headed or headwater, and forested or logged). Average daily fluctuations (maximum – minimum; °C), downstream cooling (daily mean upstream – downstream temperatures; °C), and the number of streams (n) are also included for each category. Positive (negative) values for stream cooling indicate that the stream cooled (warmed) through the study section. Temperature differences (°C) between forested and logged sub-headings for each of the lake-head and headwater categories are listed, and positive (negative) differences indicate that the logged streams were warmer (cooler) than the forested streams. Temperature data for each of the four categories represent averages covering the period from June 01 to August 31 2002.

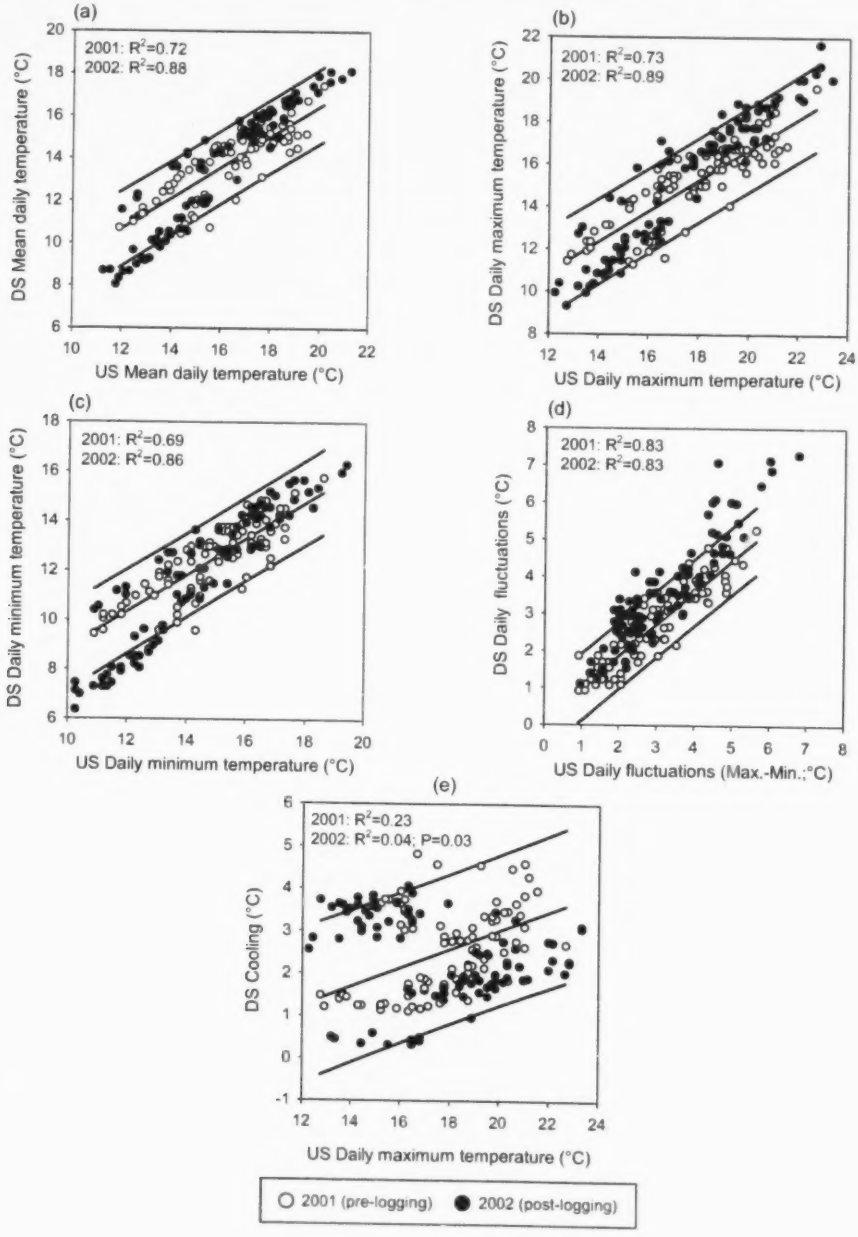
Category	Canopy cover (%)	Mean	Maximum	Minimum	Fluctuation	Cooling
Lake-headed streams: forested (n = 4)	80.25	11.54	12.67	10.42	2.25	1.35
Lake-headed streams: logged (n = 4)	55.45	12.02	14.05	10.16	3.89	1.08
Difference between forested and logged streams		0.48	1.38	-0.26	1.64	-0.27
Headwater streams: forested (n = 9)	76.98	7.37	8.04	6.75	1.29	-0.14
Headwater streams: logged (n = 3)	70.23	7.96	9.18	6.96	2.22	-0.07
Difference between forested and logged streams		0.59	1.14	0.21	0.93	0.07

During the summer of 2001 (prior to logging), lake-headed Bridge Creek was relatively heavily shaded by streamside vegetation (with a canopy cover of 88%), and the stream was relatively warm (with an average summertime maximum US temperature of 18 °C) and exhibited an average summertime downstream cooling of 2.5 °C (Table 4). During this pre-logging summer, DS daily mean, maximum, and minimum temperatures, as well as DS daily fluctuations, were strongly correlated with their US counterparts, with R^2 values ranging from 0.69 to 0.89 and all regressions significant at the $P < 0.001$ level (Figure 3). DS cooling was also significantly ($P < 0.001$) correlated with US maximum temperatures, although with a lower R^2 value of 0.23 (Figure 3). The use of regressions and prediction intervals based on the pre-harvest data allowed for an assessment of the magnitude of any temperature changes during the following post-logging summer. The logging treatment applied to Bridge Creek in early 2002 resulted in a reduction in summertime canopy cover of ~ 26% (Table 4), and relations between US and DS summertime temperature trends in 2002 remained highly significant and had R^2 values similar to those exhibited by the 2001 regressions, the exception being the relation between US maximum temperatures and DS cooling where only a weak relation was found (Figure 3). The post-logging reduction in streamside canopy cover resulted in only relatively minor changes in DS daily mean, maximum, and minimum temperatures, as well as in daily DS fluctuations and cooling (as shown by the majority of the 2002 post-logging data falling within the 2001 pre-logging prediction bands; Figure 3). For example, summertime DS daily mean temperatures increased by an average of 0.05 °C, daily maximum temperatures by 0.4 °C, and daily fluctuations by 0.7 °C following logging (Table 4). By contrast, summertime daily minimum temperatures and downstream cooling decreased by an average of 0.3 °C and 0.1 °C, respectively (Table 4). The greatest post-logging deviations from the pre-harvest regressions tended to occur during late July and during August 2002, suggesting that the greatest post-logging temperature impacts are felt during this period (Figure 3).

Table 4. Canopy cover and average daily mean, maximum, and minimum temperatures (°C) recorded at the upstream (US) and downstream (DS) sites of Bridge Creek monitored during the pre- (2001) and post- (2002) harvest summers (June 01 to August 31). Average daily fluctuations (maximum – minimum) and downstream cooling (daily mean US – DS temperatures) (°C) are also included for each period. Positive values for stream cooling indicate that the stream cooled through the study section. The average net differences between observed post-harvest DS mean, maximum and minimum temperatures, diurnal fluctuations, and stream cooling, and those predicted by the pre-harvest regressions are also included (see Figure 3). A positive (negative) difference represents an overall average increase (decrease) in the temperature trend relative to 2001.

		Upstream					Downstream				
Year	Canopy cover (%)	Mean	Maximum	Minimum	Fluctuation		Mean	Maximum	Minimum	Fluctuation	Cooling
2001	88.1	16.3	17.7	14.8	2.9		13.8	15.0	12.4	2.6	2.5
2002	65.3	16.0	17.6	14.4	3.1		13.6	15.3	11.8	3.5	2.4
						Post-logging difference	0.05	0.38	-0.31	0.66	-0.09

Figure 3. Relations between upstream (US) and downstream (DS) daily mean, maximum, and minimum temperatures, as well as between US and DS daily fluctuations (daily maximum-minimum temperatures), for lake-headed Bridge Creek. Relations between US daily maximum temperatures and DS cooling (daily mean US - DS temperatures) are also shown. For each relation, summertime (June 01 to Aug. 31) daily temperature data from 2001 (pre-logging phase) are plotted along with an associated regression line and 95% prediction intervals. Summertime temperature data for the post-logging period (2002) are superimposed on the same graphs. Regression coefficients of determination (R2) are included for each of the temperature relations for both years. Except for panel (e), all regression probability (P) values are < 0.001. Note that axis scales are not consistent.



Tests of the predictive cooling model

Using complete summertime temperature and canopy cover data collected in 2002 from the 18 independent streams and the 2 streams previousiy monitored by Mellina et al. (2002), the cooling model (equation 1) predicted with relative accuracy the average daily summertime downstream cooling or warming in the study streams, with an average absolute deviation from the line of correspondence of 0.36 °C (range 0.02 °C – 0.96 °C; Table 5, Figure 4a). The model was most accurate when applied to headwater (both forested and logged) and forested lake-headed streams, with average absolute deviations from the line of correspondence of 0.31 °C, 0.32 °C, and 0.29 °C, respectively, and it was least accurate when applied to the logged lake-headed streams (where an average absolute deviation from the line of correspondence of 0.60 °C was observed; Table 5, Figure 4a).

Table 5. Observed summertime (June 01 to Aug. 31) downstream (DS) cooling or warming for the 20 streams monitored during 2002 versus that predicted by the Mellina et al. (2002) and Brown (1985) models. The net difference (°C) between predicted and observed cooling for each stream and for each model was calculated as (predicted – observed cooling), and a negative (positive) value indicates that the model underestimates (overestimates) the observed cooling or warming. Blank cells indicate those streams for which no discharge data were obtained and for which no predictions could be made using the Brown (1985) mixing model.

Stream	Observed DS cooling (°C)	Predicted DS cooling (°C)			
		Mellina et al. (2002) model	Net difference	Brown (1985) model	Net difference
Headwater streams: forested					
RB8	-0.15	-0.01	0.14	0.07	0.22
Rot1	-0.06	-0.50	-0.44	-0.08	-0.02
T10	-0.2	-0.60	-0.40	-0.01	0.19
DV1	-0.07	-0.29	-0.22	-0.04	0.03
Bowron C1	-0.02	-0.69	-0.67	-	-
Bowron T1	0.02	0.05	0.03	-	-
Bowron T2	-0.05	-0.36	-0.31	-	-
Bowron T3	-0.41	-0.77	-0.36	-	-
Chuchinka	-0.37	-0.20	0.17	-	-
Headwater streams: logged					
Thursday	-0.16	-0.77	-0.61	0.01	0.17
SK2	0.13	-0.12	-0.25	0.09	-0.04
Emily2	-0.2	-0.11	0.09	0.01	0.21
Lake-headed streams: forested					
Willow 6	0.87	1.34	0.47	0.82	-0.05
Airline	1.79	1.76	-0.03	1.68	-0.11
T12.5	0.74	0.76	0.02	0.67	-0.07
Keves	1.99	1.34	-0.65	2.05	0.06
Lake-headed streams: logged					
Bridge	2.39	1.75	-0.64	2.31	-0.08
118/48	1.72	1.44	-0.28	0.73	-0.99
118/16	1.33	1.87	0.54	2.30	0.97
Whitefish	-1.1	-2.06	-0.96	0.02	1.12

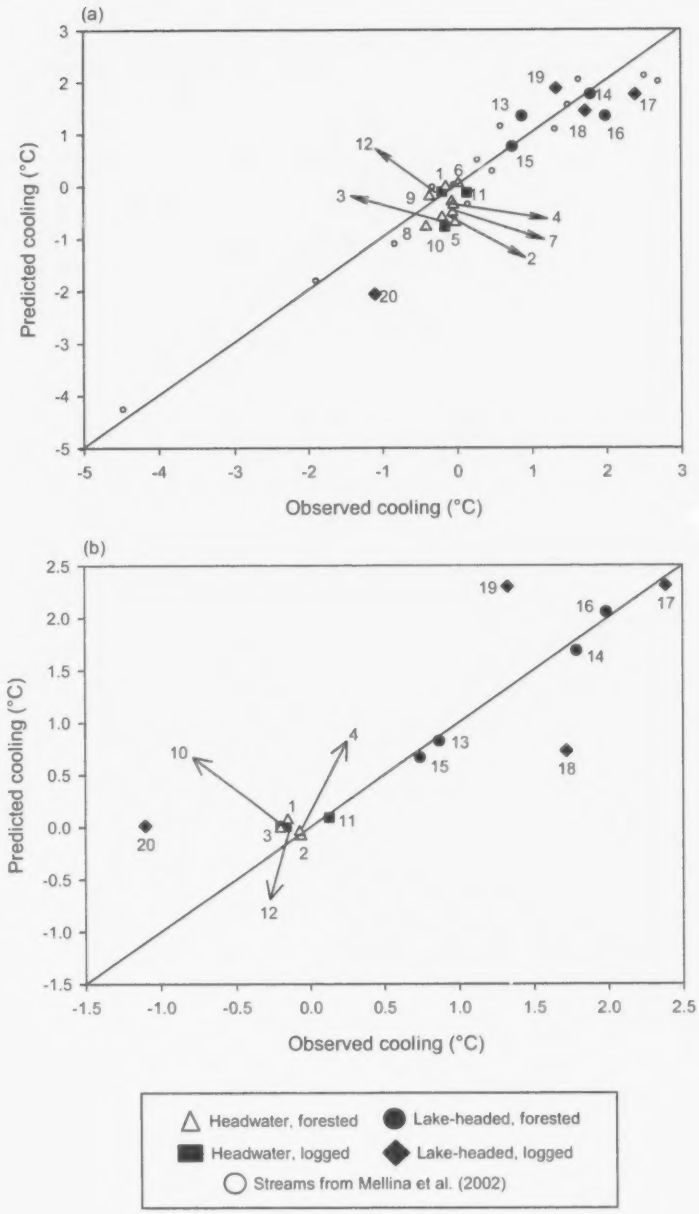


Figure 4. Predicted versus observed average summertime (June 01 to Aug. 31) cooling (daily mean upstream-downstream temperatures) for the predictive cooling and mixing models. In panel (a), the cooling model developed by Mellina et al. (2002) (equation 1) was tested using summertime stream temperature and canopy cover data collected from the 20 streams monitored during this study. Data from the streams monitored by Mellina et al. (2002) are shown for comparative purposes. In panel (b), predicted cooling was calculated by applying Brown's (1985) mixing model (equation 2) to 15 of the study streams from which discharge measurements were taken. Streams are identified according to their category, and the numbers within each panel correspond to the stream numbers listed in Table 1. The lines of correspondence (1:1) are shown in each panel, and positive (negative) values for cooling indicate stream cooling (warming) through the study reaches.

Discharge measurements taken in 15 of the 20 study streams revealed that flows increased from US to DS sites in all of the measured streams (indicating a net accrual of groundwater between the study boundaries), although the relative contributions of groundwater to DS flows varied considerably across streams and ranged from 0.4% – 30% (Table 6). Using observed stream temperature and discharge data and an average groundwater temperature of 6.75 °C reported by Mellina et al. (2002), Brown's (1985) mixing model (equation 2) also predicted with relative accuracy the average daily summertime downstream cooling or warming in the study streams, with an average absolute deviation from the line of correspondence of 0.29 °C (range 0.02 °C – 1.12 °C; Table 5, Figure 4b). The mixing model was also least accurate when applied to the logged lake-headed streams (where an average absolute deviation from the line of correspondence of 0.79 °C was observed), and it was most accurate when applied to the remaining categories (which showed average absolute deviations from the line of correspondence of 0.07 °C – 0.14 °C; Table 5, Figure 4b).

Table 6. Discharge estimates (L•s-1) for 15 streams obtained during the month of September 2002. US and DS refer to upstream and downstream sites, respectively. The difference in discharge is the difference between US and DS flows, and represents net groundwater inputs. The percentage of DS flows contributed by groundwater was calculated as: (the difference in discharge/DS discharge)•100.

Stream	US discharge	DS discharge	Difference	Percentage of DS flows contributed by groundwater (%)
Headwater streams: forested				
RB8	0.89	0.95	0.06	6.32
Rot1	1.86	2.03	0.17	8.37
T10	8.62	8.74	0.12	1.37
DV1	10.69	11.7	1.01	8.63
Headwater streams: logged				
Thursday	47.19	47.38	0.19	0.40
SK2	1.56	1.9	0.34	17.89
Emily2	1.32	1.35	0.03	2.22
Lake-headed streams: forested				
Willow 6	1.91	2.18	0.27	12.39
Airline	0.67	0.86	0.19	22.09
T12.5	3.33	3.92	0.59	15.05
Keves	0.85	1.31	0.46	35.11
Lake-headed streams: logged				
Bridge	0.24	0.32	0.08	25.00
118/48	2.5	2.75	0.25	9.09
118/16	0.56	0.8	0.24	30.00
Whitefish	0.67	0.69	0.02	2.90

Note: No discharge data were available for the five headwater streams monitored by the B.C. Ministry of Forests.

When tested using restricted monthly temperature data, the cooling model continued to predict with relative accuracy the average amount of summertime DS cooling or warming in the 20 study streams, although with a greater mean and range in absolute deviations from the line of correspondence when compared to predictions made using complete summertime data (Table 7, Figure 5). The most accurate predictions were obtained when data from the months of July and August were used (where mean deviations of 0.36 °C and 0.40 °C, respectively, were observed), whereas the worst predictions were obtained when data from the month of June were used (mean deviation of 0.66 °C; Table 7). In all three months, logged lake-headed streams again yielded the least accurate predictions when compared to the remaining three categories (Figure 5). When using maximum US temperatures collected during the course of a single day, the model also predicted with relative accuracy the average amount of summertime DS cooling or warming in the 20 study streams, with an average absolute deviation from the line of correspondence of 0.62 °C (range 0.01 °C – 2.53 °C for all 180 iterations of the model; Table 7, Figure 6). Furthermore, results from the model iterations revealed that the model's accuracy tended to decrease when daily temperature data from early to mid-June were used, but that its accuracy remained relatively consistent when data from late June to the end of August were used (Table 7; Figure 6). For example, the average absolute deviation from the line of correspondence using data from June 05 and June 15 was ~ 1.0 °C, compared to an average deviation of only 0.50 °C when data from June 25 onwards were used (Table 7).

Table 7. Test of the predictive cooling model developed by Mellina et al. (2002) using complete summertime (June 01 to Aug. 31) and restricted (monthly and selected daily) stream temperature data collected during 2002. For each of the indicated periods, the model was applied to all 20 streams using the average (or daily) maximum upstream temperature recorded during each time interval together with the canopy cover values presented in Table 1. The mean, maximum, and minimum absolute deviations (°C) from the cooling model predictions (calculated as the absolute value of predicted – observed downstream cooling or warming) are presented for each time interval.

Date (2002)	Mean deviation	Maximum deviation	Minimum deviation
Summer data			
June 01 - Aug. 31	0.36	0.96	0.02
Monthly data			
June	0.66	1.55	0.01
July	0.36	1.55	0.00
August	0.40	1.36	0.03
Daily data			
June 05	1.21	2.53	0.05
June 15	0.77	1.70	0.01
June 25	0.53	1.35	0.05
July 05	0.62	1.39	0.03
July 15	0.35	1.43	0.01
July 25	0.65	2.02	0.01
August 05	0.56	1.42	0.03
August 15	0.43	1.46	0.01
August 25	0.44	1.35	0.03

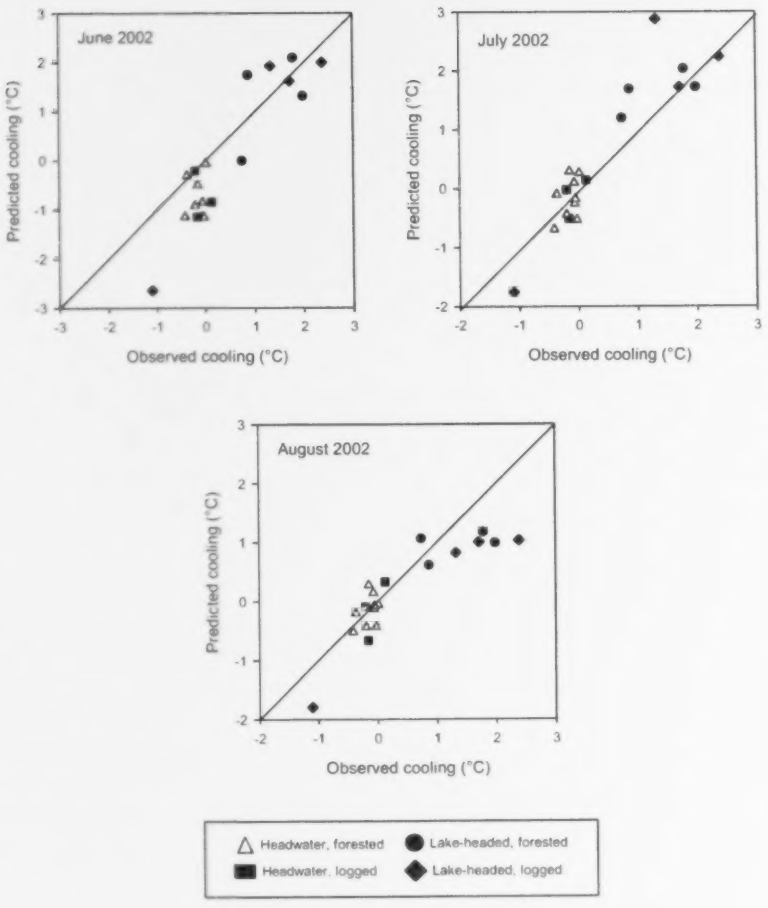
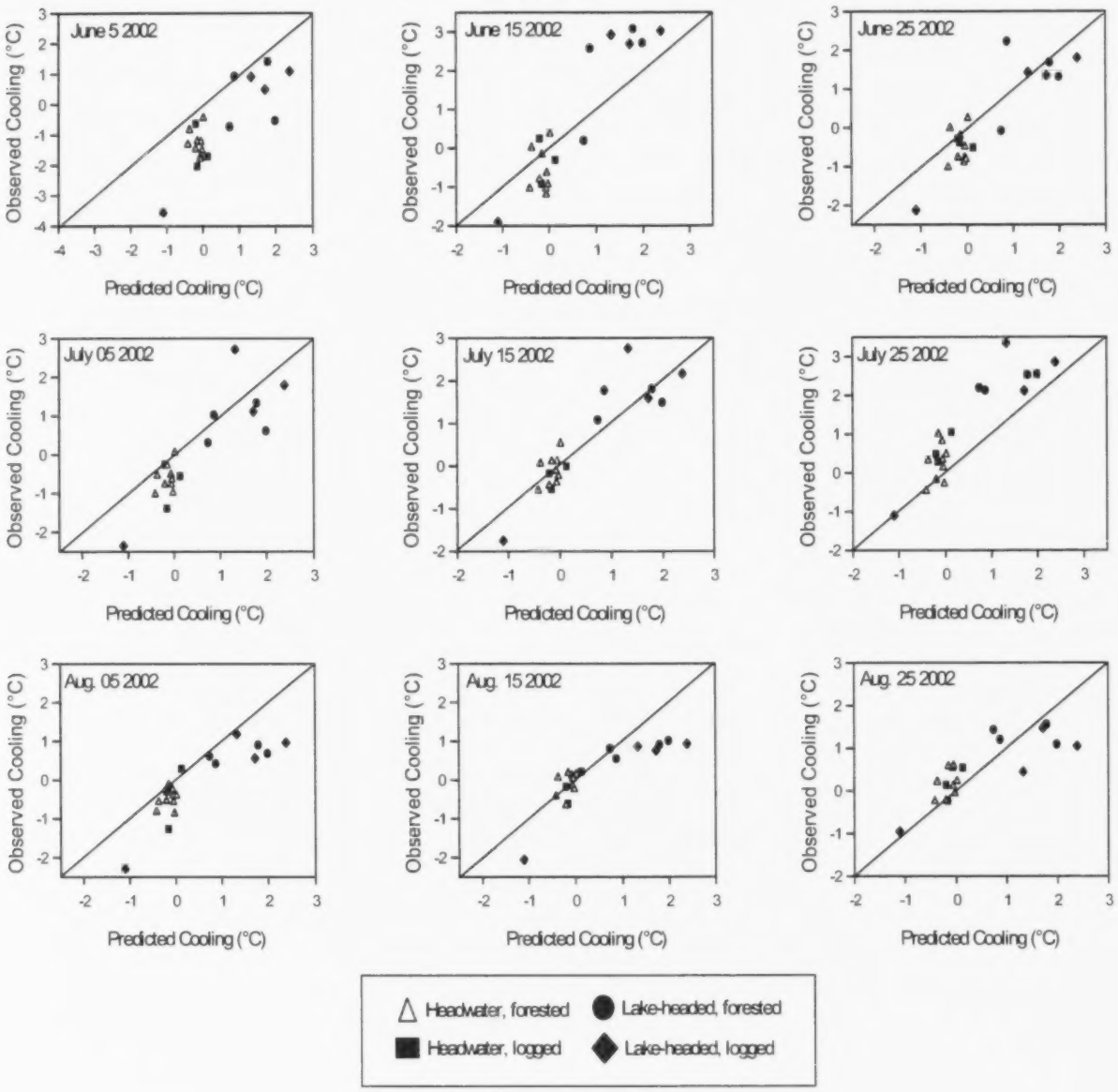


Figure 5. Test of the predictive cooling model (equation 1) using restricted monthly data. In each panel, predicted downstream cooling (daily mean upstream – downstream temperatures) for each stream was calculated by substituting the maximum upstream temperature averaged over the indicated month into the cooling model and compared against the observed average summertime (June 01 to Aug. 31 2002) cooling. A positive (negative) value for cooling indicated that the stream cooled (warmed) as it flowed downstream. Stream-specific canopy cover data (Table 1) were used in all model iterations. Streams are further identified according to their category, and the lines of correspondence (1:1) are shown in each panel.

Figure 6. Test of the predictive cooling model (equation 1) using restricted daily temperature data. In each panel, predicted downstream cooling (daily mean upstream-downstream temperatures) for each stream was calculated by substituting the maximum upstream temperature recorded on the indicated day into the cooling model and compared against the observed average summertime (June 01 to Aug. 31 2002) cooling. A positive (negative) value for cooling indicated that the stream cooled (warmed) as it flowed downstream. Stream-specific canopy cover data (Table 1) were used in all model iterations. Streams are further identified according to their category, and the lines of correspondence (1:1) are shown in each panel.



Lastly, the combination of temperature and canopy cover data from the 14 streams originally monitored by Mellina et al. (2002) and those from the 18 independent streams monitored during this study yielded a new global predictive cooling model with a coefficient of determination (0.91) and standard error of the estimate (0.41) that were similar to those of the original model (0.95 and 0.40, respectively; Table 8). Furthermore, the global model retained the same predictor variables as the original model (both of which remained highly significant at the $P < 0.001$ level), and the predictor coefficients (together with the model intercept) were also similar to those of the original model (Table 8). Validation of the global model using the PRESS procedure revealed a relatively close agreement between the PRESS value (6.7) and the model's SSE (4.8), which supports the new model's predictive capability. The global model also predicted with relative accuracy the average daily summertime DS cooling or warming in all 32 streams, with an average absolute deviation from the line of correspondence of 0.32 °C (range 0.001 °C – 0.74 °C;.

Table 8. Comparison of predictor coefficients and their probability (P) values, as well as overall model coefficients of determination (R2 values), standard errors of the estimate, and P values for the original predictive cooling model developed by Mellina et al. (2002) and the global model developed using a combination of the 14 streams monitored by Mellina et al. (2002) and the 18 independent streams monitored during this study.

Model	Constant	Maximum US temperature		Canopy cover		Model R^2	Model standard error of the estimate	Overall model P value
		Coefficient	P value	Coefficient	P value			
Mellina et al. 2002 (n=14)	-9.9	0.25	< 0.001	4.0	< 0.001	0.95	0.40	< 0.001
Global model (n=32)	-9.4	0.23	< 0.001	3.9	< 0.001	0.91	0.41	< 0.001

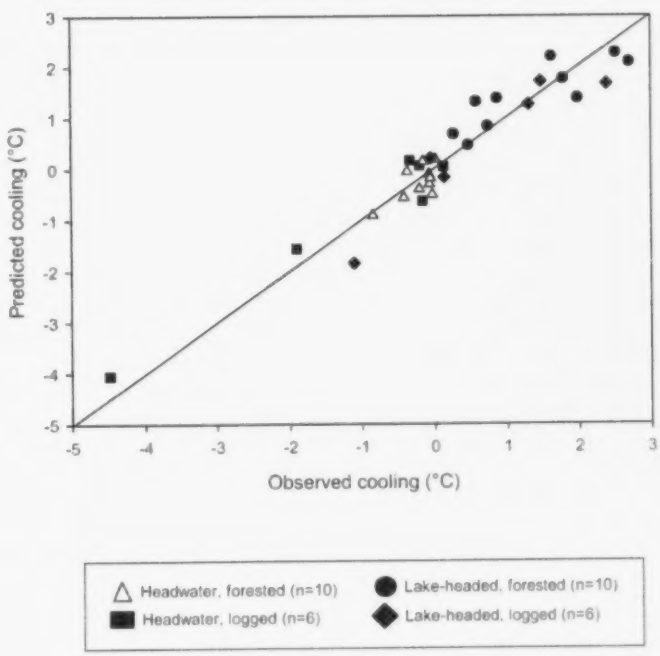


Figure 7. Predicted versus observed average summertime (June 01 to Aug. 31) downstream cooling (daily mean upstream – downstream temperatures) for the global cooling model developed using a combination of the 14 streams monitored by Mellina et al. (2002) and the 18 independent streams monitored during this study. A positive (negative) value for cooling indicated that the stream cooled (warmed) as it flowed downstream. The line of correspondence (1:1) is shown, and streams are identified according to their category (with the number of streams in each category shown in the legend).

Discussion

Comparisons between lake-headed and headwater streams

The temperature patterns exhibited by the 20 study streams support the observations made by Mellina et al. (2002) that lake-headed streams are generally warmer at their US sites and exhibit greater daily fluctuations when compared to headwater streams, and that these streams generally cooled (and headwater streams warmed) as they flowed downstream, regardless of whether or not the riparian canopy had been harvested. The presence of the small, fully exposed lakes and swamps were shown by Mellina et al. (2002) to promote warm initial temperatures in outlet streams, thereby creating thermal conditions that are conducive to downstream cooling via groundwater inflow. However, stream Whitefish appeared to be an anomaly, as it was the only lake-headed stream in which a considerable amount of DS summertime warming was observed. Stream Whitefish's US study boundary was 1250 m from the lake outlet, whereas the remaining lake-headed streams had US boundaries that were ≤ 200m from their respective outlets. This distance likely diminished the influence of Whitefish's headwater lake on US temperatures, as shown by the average summertime US maximum temperature of ~ 8 °C (which is consistent with the average maximum of 8.3 °C exhibited by the headwater streams), compared to US maxima of between 13 °C – 18 °C in the remaining lake-headed streams. This highlights the fact that the presence of headwater lakes does not necessarily result in downstream cooling, but rather that headwater lakes promote warm temperatures relatively close to their outlets, and that their influence on outlet temperature regimes declines with distance (Mellina et al. 2002). The relatively long distance between the US site of stream Whitefish and the lake outlet therefore likely resulted in maximum US summer temperatures that were not sufficiently elevated to favor stream cooling between study boundaries via groundwater inputs. Downstream warming in stream Whitefish was also likely augmented because it was harvested and retained only 29% canopy cover, and had the stream been forested (with an average canopy cover of 80%) the cooling model predicts that this stream would have exhibited an average summertime DS warming of only 0.3 °C (a value that is again consistent with those recorded in the forested headwater streams).

The differences in daily mean, maximum and minimum temperatures, as well as in daily fluctuations and downstream cooling, were approximately equal when comparing the forested and logged states of lake-headed and headwater streams, and this appears to contradict the observations of Mellina et al. (2002) that post-logging temperature changes in lake-headed streams are less severe than those in headwater streams. However, the magnitude of any post-logging changes must be assessed in terms of reductions in streamside canopy cover, which influences the amount of solar radiation (the dominant energy source) reaching the stream bottom (Brown 1985). The logged headwater streams in this study only experienced canopy cover reductions of ~ 9% when compared to their forested counterparts, whereas the logged lake-headed streams experienced reductions of ~ 31% relative to their forested counterparts. The modest canopy cover reductions in the logged headwater streams therefore likely buffered the anticipated temperature increases. Furthermore, the cooling model (equation 1) can be used to predict the expected temperature increases in the logged headwater streams had they experienced reductions in canopy cover similar to those seen around the logged lake-headed streams. For example, using average summertime US maximum temperatures recorded in the logged headwater streams and an average canopy cover of 54% (representing a reduction of 30% relative to the forested headwater streams), the cooling model predicts that the logged headwater streams would have exhibited an average summertime DS warming of 0.72 °C along with an average summertime DS daily mean temperature of 8.6 °C. Differences in average DS daily mean temperatures and warming between logged and forested headwater streams under these conditions yield values of 1.31 °C and 0.58 °C, respectively, which represent increases of 2 to 2.75 times those seen in the lake-headed streams. Results from Bridge Creek also provide evidence that lake-headed streams experience less severe post-logging temperature increases when compared to headwater streams. Bridge Creek exhibited relatively modest summertime post-logging temperature changes (averaging 0.05 °C – 0.66 °C) with respect to daily mean,

maximum and minimum temperatures, as well as daily fluctuations and stream cooling, following the removal of ~ 25% of the streamside timber. These values are consistent with those reported by Mellina et al. (2002) for lake-headed streams 118/48 and 118/16 (where average summertime changes of 0.05 °C – 1.1 °C were observed for the same temperature parameters after ~ 50% of the canopy was removed), but which contrast sharply with those reported in the literature for headwater streams (where average increases of ~ 5 °C – 7 °C have been reported for daily mean, maximum and minimum temperatures; Mellina et al. 2002). The data presented above therefore support the observation made by Mellina et al. (2002) that, with respect to post-logging temperature responses, lake-headed streams may be able to support a more aggressive level of streamside timber harvesting, provided that US cutblock boundaries remain relatively close to the lake outlets in order to retain the thermal influence of the lentic waterbodies.

Tests of the predictive cooling model

The cooling model (equation 1) predicted with relative accuracy the amount of downstream cooling and warming observed in all 20 study streams (with no obvious outliers deviating from the line of correspondence), suggesting that the model was applicable to streams that span the range in physical characteristics encountered in the data set. The absolute deviations from the line of correspondence (mean of 0.36 °C, range 0.02 °C – 0.96 °C) also compare favorably with values reported by Mellina et al. (2002) for their model development dataset (mean 0.3 °C, range 0.07 °C – 0.6 °C). The relatively close correspondence between predicted and observed downstream cooling or warming in the 18 independent streams and in the 2 streams previously monitored by Mellina et al. (2002) therefore provides support for the model's predictive capability across space and across time. Furthermore, the close correspondence between observed cooling or warming and that predicted from the mixing model (equation 2) suggests that groundwater inputs were important determinants of downstream temperatures in the 15 streams from which discharge data were obtained. For example, cooling in the lake-headed streams was likely accomplished primarily via a combination of warm initial temperatures (promoted by the headwater lakes) and cold groundwater inputs, whereas warming in the headwater streams suggests that the temperature regimes of these streams were controlled by effluent groundwater inputs (Hewlett and Fortson 1982). Lastly, the discharge data revealed that groundwater inflows were present in all measured streams, and this suggests that the presence of groundwater may be a necessary condition if the model is to be used for predictive purposes.

The cooling model (equation 1) was least accurate when applied to logged, lake-headed streams, with deviations that were ~ 2 times those for the remaining categories. It underestimated the observed cooling in three of the four streams in this category, which suggests that confidence in its predictive abilities may be lessened when applied to these stream types. The reasons for the increased post-logging cooling observed in these streams are unknown given that no detailed hydro-meteorological data were collected, but they may be related to the thermodynamic conditions that promote cooling. For example, cooling mediated via inputs of cold groundwater increases with increasing stream temperature, and is greatest when the temperature difference between the surface water and groundwater is large (Brown 1985). Increased groundwater flows have been shown to accompany logging (Troendle and King 1985), which would in turn promote increased cooling when mixed with the warm surface waters found in lake-headed streams. Furthermore, Silliman and Booth (1993) found that bed temperature gradients are greater in areas of groundwater inflow, thus promoting heat loss via conduction and hyporheic exchange and contributing to downstream cooling. Lastly, post-logging reductions in canopy cover that increase stream temperatures might also enhance groundwater-mediated cooling, provided that surface temperatures become sufficiently elevated. Because the surface waters in outlet streams close to their headwater lakes are initially warm, post-logging temperature increases (even though these may be modest) may therefore enhance groundwater-mediated cooling in these stream types. The same conditions would not be expected to apply to the logged streams monitored during this study that had relatively cold initial surface water temperatures (such as

lake-headed stream Whitefish and the logged headwater streams), because the logging treatments did not result in sufficiently elevated temperatures to promote downstream cooling via groundwater inputs.

The cooling model remained relatively accurate when restricted data (i.e., temperatures from only a single month or day) were used, but its predictions were less accurate than those generated using complete summertime data. The model iterations also showed that, in the event that only limited temperature data are available, the model's predictions are most accurate if data are collected from the middle of June onwards. Therefore, although complete summertime temperature data are preferable, restricted data may be sufficient for certain management objectives that can tolerate the concomitant reduction in accuracy. Lastly, the global cooling model generated by combining the 14 streams monitored by Mellina et al. (2002) and the 18 independent streams monitored during this study support the validity and robustness of the original cooling model (equation 1), given that a doubling of the data set resulted in similar values for the model intercepts, predictor coefficients, R^2 values, standard errors of the estimate, and the overall probability values.

Management implications

Increases in stream temperature following logging are generally considered to be detrimental to fish development, physiology, behaviour, and activity (Beschta et al. 1987). For example, temperatures that exceed fish thermal preferences and optima lead to increased metabolic requirements and to decreased food conversion efficiencies and dissolved oxygen levels in water (Spigarelli and Thommes 1979). However, water temperatures that are too cold can impede growth and development in stream-resident fish, and in northern, temperate latitudes small streams may be so well shaded and consequently so cold that fish growth is stunted, even for cold-water adapted species like trout (Anderson 1973; Brownlee et al. 1988). Modest increases in stream temperature in these cases may lead to increases in primary and secondary productivity, as well as increases in fish activity levels, digestion and food conversion rates (Gregory et al. 1987; Jobling 1981), and these effects are expected to enhance growth as long as temperatures do not exceed the tolerance limits of the species being considered. An assessment of whether any predicted stream temperature increases are deemed acceptable must therefore be assessed in terms of the fish species that are likely to be affected. For example, within the Takla watershed in north-central B.C., sockeye salmon (Oncorhynchus nerka) spawn in their natal streams in late summer, with fry emergence and emigration occurring during the following spring. It has been speculated that increases in stream temperature would lead to accelerated development to the fry stage and earlier, possibly untimely, emergence and emigration when environmental conditions are potentially unsuitable (Macdonald et al. 1998). However, the same forecast does not necessarily hold true for a species like rainbow trout (O. mykiss), which typically spawn in the spring with fry emerging from stream gravels by mid to late summer. Modest stream temperature increases could also lead to earlier fry emergence, but because rainbow trout are spring spawners the advanced timing would allow fry additional time to grow and accumulate energy reserves before the onset of winter, thereby conferring a size advantage and increasing the likelihood of overwinter survival (Quinn and Peterson 1996).

In addition to effects on emergence times, other criteria (such as species-specific thermal tolerances and growth optima) are also important fisheries management considerations that must be taken into account when assessing logging impacts. For example, the range of temperatures for optimum growth (i.e., the range within which growth is maximized) for rainbow trout is 15.5 °C to 17.3 °C in a thermally fluctuating environment (Hokanson et al. 1977). The average summertime DS daily mean temperature (which may be a more appropriate indicator than maximum temperature; Diana 1995) of the logged streams monitored during this study, ranging from 7.2 °C to 9.3 °C for the headwater streams and 8.4 °C to 13.6 °C for the lake-headed streams, would therefore likely not be detrimental for rainbow trout growth. Even if the forested streams were to experience an 85% reduction in canopy cover as a result of streamside logging,

the cooling model (equation 1) predicts that the average summertime DS mean daily temperature would increase to 9.5 °C to 12.8 °C for the headwater streams, and from 13.7 °C to 15.9 °C for the lake-headed streams, levels that are still generally below the growth optimum for this species. However, temperature increases that are beneficial to one fish species may be detrimental to another. For example, bull trout (Salvelinus confluentus) have thermal preferenda that differ from those of rainbow trout, as they prefer temperatures below 15 °C and are generally less tolerant of warm temperatures (Bonneau and Scarnecchia 1996). Therefore, even modest temperature increases may negatively affect this species.

The catastrophic mountain pine beetle epidemic appears firmly entrenched in north-central B.C., with large-scale clearcut logging often the only effective control for severe beetle infestations in the middle of epidemic areas. Measures to contain the epidemic through timber harvesting raises the possibility that stream temperatures may increase in cases where clearcutting within riparian zones becomes unavoidable. Given that canopy cover is one of the cooling model predictors and is a variable that is expected to change following logging, the model may prove useful to fisheries and forestry managers by allowing them to assess the severity of any temperature changes that can be expected following logging in small headwater and lake-headed streams. To illustrate the cooling model's potential application, a forested stream with 80% canopy cover between proposed cutblock boundaries and an average pre-logging summertime maximum US temperature of 12 °C is predicted to cool by an average of 0.7 °C over the summer when unharvested, resulting in an average DS summertime mean daily temperature of 11.3 °C. The model further predicts that streamside logging that removed 50% of the riparian timber would result in an average summertime DS warming of 0.5 °C (and a mean daily DS temperature of 12.5 °C), whereas the removal of 90% of the riparian timber would result in a warming of 3.3 °C and a mean daily DS temperature of 15.3 °C. Fisheries and forestry managers working in concert can then assess whether any projected temperature changes would be beneficial or detrimental to resident fish species inhabiting the stream, and consequently plan timber harvesting activities accordingly.

Conclusions

The results presented above provide evidence that the presence of small, shallow, fully exposed lentic waterbodies (lakes or swamps) results in relatively warm temperatures in sub-boreal outlet streams when compared to headwater streams, and consequently creates thermal conditions that are conducive to downstream cooling via groundwater inflow. Furthermore, the comparative survey revealed that downstream cooling was widespread among the lake-headed streams, and downstream warming was prevalent in the headwater streams, regardless of whether or not the riparian zones were harvested. The data also suggested that temperature increases following streamside timber harvesting around lake-headed streams were more modest when compared to headwater streams, and that these increases may have largely been mitigated by a combination of the influence of the headwater lakes on outlet thermal regimes together with cold groundwater inputs. These stream types may consequently support a more aggressive level of streamside timber harvesting, provided that logging activities are conducted relatively close to the outlets and that groundwater inputs are present.

Whereas predicting stream temperature responses to logging is a complex undertaking, given the myriad possible interactions among energy budget components (Adams and Sullivan 1989), the cooling model developed by Mellina et al. (2002) has potential as a simple, cost-effective risk management tool that would allow planners to predict post-logging downstream temperature trends in small, lake-headed and headwater streams in boreal and sub-boreal regions using easily measured variables. The model's overall simplicity makes it an attractive and potentially useful alternative to the detailed hydro-meteorological energy budgets that are typically required for predicting changes in stream temperature (Sullivan et al. 1990; Evans et al. 1998). Furthermore, after being subjected to the testing presented above, the model's predictive

capabilities across both space and time, as well as its apparent robustness when confronted with limited temperature data, will likely increase confidence in its application to management issues. However, Brown's (1985) mixing model results suggest that groundwater inputs were important determinants of downstream temperature trends in the streams monitored during this study, and it is therefore possible that such inflows are a necessary requirement in order for the model to be applied successfully. Furthermore, the relative importance of groundwater inputs declines in larger streams (Sullivan et al. 1990), and the model and its mechanistic suppositions may consequently be restricted to small streams that span the range of physical characteristics encountered in the above dataset and in the one used by Mellina et al. (2002). Lastly, although both the cooling and mixing models (equations 1 and 2) were able to predict downstream cooling or warming in the study streams with similar accuracy, the cooling model developed by Mellina et al. (2002) may be more useful for management applications because the predictor variables are more easily measured, and because there is some confidence in the model's predictive capability when using data from a variety of restricted time intervals. By contrast, stream discharge measurements were only taken on a single day, and the temporal variability in discharge and in contributions of groundwater to DS flows remains largely unknown in the study streams. Consequently, the accuracy of Brown's (1985) mixing model remains untested when subjected to data originating from restricted summertime periods.

Although the majority of studies examining stream temperature responses to logging have been conducted in coastal regions, much of the future timber supply in the northern hemisphere is expected to come from boreal and sub-boreal forests in temperate regions (Bryant et al. 1997). Unfortunately, relatively few studies that investigate stream temperature responses to timber harvesting have been conducted in these regions (for examples see Slaney et al. 1977, Brownlee et al. 1988, Macdonald et al. 1998, Mellina et al. 2002, and Macdonald et al. 2003), and even fewer have focused on lake-headed streams. The results presented above are directly applicable to fisheries and forestry management issues in north-central B.C. (and possibly in other regions sharing similar geo-climatic conditions), and provide much-needed information that will allow resource managers to make scientifically defensible decisions. For example, in an effort to contain the mountain pine beetle epidemic, knowledge of the general temperature patterns of small headwater and lake-headed streams (and of their potential responses to clearcut logging) will allow resource managers to plan appropriate timber harvesting activities that will minimize the potential impacts on stream-dwelling fish. Further research is encouraged to determine if the cooling model can accurately predict downstream cooling or warming in streams from other climatic regions, as well as its reliability in management applications when applied towards forecasting potential post-logging temperature changes.

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